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This is a U.S. Patent Application for:

Title Line #1:	*	PHASE NOISE COMPENSATION
Title Line #2:	*	IN AN INTERFEROMETRIC SYSTEM

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PHASE NOISE COMPENSATION
IN AN INTERFEROMETRIC SYSTEM

TECHNICAL FIELD

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The invention relates generally to obtaining measurements for optical characteristics of a device under test and more particularly to canceling phase noise from measurements of group delay introduced by the device under test.

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BACKGROUND ART

Techniques for testing or analyzing optical components are known. A "device" under test (DUT), such as a length of fiber optic cable, may be carefully tested for faults or may be analyzed to determine whether 15 the device is suitable for use in a particular application. System components such as multiplexers, demultiplexers, cross connectors, and devices having fiber Bragg gratings may be separately tested before a system is assembled.

Optical testing may be performed using a heterodyne optical 20 network analyzer. Such analyzers may be employed for measuring properties of optical components, such as group delay. "Group delay" is sometimes referred to as envelope delay, since it refers to the frequency-dependent delay of an envelope of frequencies, with the group delay for a particular frequency being the negative of the slope of the phase curve at that fre- 25 quency. Typically, a heterodyne optical network analyzer includes two interferometers. An example of a heterodyne optical network analyzer 10 having two interferometers 12 and 14 is shown in Fig. 1. A tunable laser source (TLS) 16 generates a laser light beam that is split by a coupler 18. The TLS is continuously tuned, or swept, between a start frequency and a 30 stop frequency. By operation of the coupler 18, a first portion of the coherent light from the TLS is directed to the DUT interferometer 12, while a second portion is directed to the reference interferometer 14.

The DUT interferometer 12 has a second coupler 22 that allows beam splitting between a first arm 24 and a second arm 26. A mirror 28 is 35 located at the end of the first arm and a DUT 20 is located near the reflective end of the second arm. The lengths of the two arms can differ, and the difference in the optical path length is represented in Fig. 1 by L_{DUT}. Since the DUT can be dispersive, the actual optical path length is a function of

frequency. A detector 30 is positioned to measure the combination of the light reflected by the mirror 28 and the light reflected at the DUT 20. Processing capability (not shown) is connected to the detector 30 to measure group delay of the DUT as a function of frequency. However, in order to very precisely measure the group delay, it is necessary to obtain knowledge of the frequency tuning of the TLS 16 as a function of time. The reference interferometer 14 is used for this purpose.

The structure of the reference interferometer 14 is similar to that of the DUT interferometer 12, but a mirror 32 takes the place of the DUT 20. A second detector 34 receives light energy that is reflected by the combination of the mirror 32 at the end of a third arm 36 and a mirror 38 at the end of a fourth arm 40. As in the DUT interferometer, the lengths of these two arms can be different, and this difference in lengths is represented by L_{REF}. The optical characteristics of the reference interferometer are fixed and known.

A potential problem occurs in the heterodyne optical network analyzer 10 when the path length difference (L_{DUT}) is sufficiently large that coherence effects become an issue. The frequency generated by the TLS 16 undesirably fluctuates in a random manner around its target frequency as it is tuned. The random fluctuations occur as a result of various quantum or stochastic effects. The random fluctuations of the frequency affect the frequency of the heterodyne interference signal measured by each detector 30 and 34. When the group delay of the DUT 20 is calculated, the frequency fluctuations of the TLS 16 manifest themselves as noise in the group delay measurement. This ultimately limits the precision of the measurement process. This effect is referred to as "phase noise." The phase noise on the measurement process increases as the path length mismatch for the two arms 24 and 26 of the DUT interferometer 12 increases, until the path length mismatch equals or exceeds the coherence length of the laser beam.

What is needed is a method and system for at least reducing the deleterious effects of phase noise in an interferometric system.

SUMMARY OF THE INVENTION

A reduction in the effects of phase noise introduced into an interferometric system is achieved by using a reference interferometer to "measure" the effects. A coherent light beam having both intentional frequency variations and undesired frequency fluctuations is divided into separate beam portions which are directed to the reference interferometer

and a test interferometer. The reference interferometer has known optical delay characteristics and the test interferometer has known or estimated optical delay characteristics, allowing a delay/phase cross-correlation for each of the two interferometers. That is, delay information regarding one of

5 the interferometers is used with phase information acquired from the other interferometer in the cancellation of phase noise effects. Typically, the method is used to eliminate the adverse effects of the phase noise within the test interferometer, but embodiments are contemplated in which the approach is used to offset phase noise effects in other components, such as a separate

10 optical system in which a third portion of the coherent light beam is directed for other purposes.

The intentional variation of the light beam frequency is provided by operation of a tuned laser source that continuously sweeps through a frequency range. On the other hand, the undesired frequency fluctuations are

15 random and occur as a result of quantum or other stochastic effects in the generation or manipulation of the light beam. These random fluctuations produce the phase noise effects.

In one embodiment, the cross-correlation approach includes determining the differences between the phase at the output of each inter-

20 ferometer at time t and the phase at the same output at the time t minus the delay of the other interferometer. That is, for each time t in a time series, a first phase difference is determined for the test interferometer and a second phase difference is determined for the reference interferometer. The first phase difference is the difference between the phase of the test output at

25 the time t and the phase at the test output at the time t offset by the known delay of the reference interferometer. The second phase difference is the difference between the phase at the reference interferometer output at time t and the phase at the reference interferometer output at time t offset by a delay representative of the delay of the test interferometer. The representa-

30 tive delay may be a calculation of the mean of the delay, as determined using other techniques. Within this embodiment, the time series may be formed by determining the difference between the first and second difference. This double-difference technique provides an isolation of the random phase noise introduced by operation of the light beam source.

35 Typically, but not critically, the test interferometer includes a device under test (DUT) for which group delay is being measured. Thus, the phase noise is used to reduce or eliminate the adverse effects of such noise in the calculation of DUT group delay. The value of mean delay that is used

in the determination of the second phase difference may be obtained using known techniques, such as optical frequency domain reflectometry (OFDR) or optical coherence domain reflectometry (OCDR).

5 An advantage of the invention is that more reliable determinations of the optical characteristics of a DUT can be achieved. Heterodyne optical network analyzers operate by splitting and then recombining a coherent light beam. When the split beams are recombined, the random frequency fluctuations of phase noise limit the precision of the measurement procedure. Thus, for a laser having a 100 kHz linewidth, the phase noise can

10 be a limiting factor in measurement precision with only a few meters of delay introduced by a DUT in the interferometer. It follows that phase noise renders measurements of group delay and group velocity dispersion for particularly long DUTs, such as 10 km lengths of fiber, necessarily unreliable. However, the phase noise reduction of the invention allows high-delay devices to be

15 analyzed.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram of a heterodyne optical network

20 analyzer which may be used in measuring optical characteristics of a device under test.

Fig. 2 is a block diagram of a system for controlling phase noise in the analyzation of optical characteristics of a device under test, in accordance with the invention.

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DETAILED DESCRIPTION

With reference to Fig. 2, a heterodyne optical network analyzer 42 having phase noise cancellation is shown as being used for measure-

30 ments of group delay, as indicated by a group delay module 44. However, the analyzer may be used for other measurements relevant to optical characteristics of a device under test (DUT), such as measurements of group velocity, transmissivity, reflectivity and chromatic dispersion. Moreover, the phase noise cancellation may be quantified using the techniques to be

35 described below, but the quantifications may be applied in other systems in which beam portions are separately conducted for comparison purposes.

The analyzer 42 is shown as including components that are the functional equivalents of components of Fig. 1. The coherent light beam that

is generated by the TLS 16 is split by a coupler 18 into beam portions that are separately directed to the test interferometer 12 and the reference interferometer 14. The interferometers 12 and 14 may be structurally identical to the ones shown in Fig. 1, but the detectors 30 and 34 are shown as being separated from the interferometers in Fig. 2. The interferometers of Fig. 2 need not be identical to the interferometers of Fig. 1. In addition to the conventional Michelson and Mach-Zehnder configurations, the invention may be used with other interferometer architectures.

In the embodiment of Fig. 2, the test interferometer 12 includes the capability of being attached to a DUT. For example, the DUT may be a length of fiber, a multiplexer, a demultiplexer, or a cross connector. The optical characteristics of the DUT will affect the characteristics of the light that reaches the test detector. However, there may be embodiments in which the optical characteristics of the test interferometer remain fixed, in the same manner as the reference interferometer 14.

As is known in the art, the TLS 16 generates swept-frequency light that is split by the coupler 18 and directed into the two interferometers 12 and 14. Each detector 30 and 34 may be a photoreceiver that measures an intensity I as a function of time t, where

$$I(t) = I_{arm1} + I_{arm2} + 2 \left(I_{arm1}\, I_{arm2} \cos \Phi(t) \right) \qquad \text{Eq. 1}$$

That is, the measured intensity is a function of the intensities of the light from the two arms and is a function of the phase of the light at time t. For group delay measurements, $\Phi(t)$ is an important component of Eq. 1.

The phase $\Phi_{TI}(t)$ measured by the test interferometer 12 at time t is

$$\Phi_{TI}(t) = 2\pi \left[\nu_0 + \gamma t - \frac{\gamma}{2}\tau_{TI} + \chi\left(t - \frac{\tau_{TI}}{2} \right) \right] \tau_{TI} + \phi(t) - \phi(t - \tau_{TI})$$

$$\text{Eq. 2}$$

$$= \omega\left(t - \frac{\tau_{TI}}{2} \right) \tau_{TI} + \phi(t) - \phi(t - \tau_{TI}) = \omega_{TI}\tau_{TI} + \phi(t) - \phi(t - \tau_{TI})$$

where the subscript "TI" indicates that the variable is associated with the test interferometer, $\omega(t)$ is the radian frequency produced by the TLS 16, ν_0 is the initial frequency of the swept laser light, γ is the rate of the linear sweep in

units of Hz/second, $\chi(t)$ represents the nonlinear components of the frequency sweep, $\phi(t)$ represents the random phase evolution associated with the finite coherence of the TLS 16, and τ_{TI} is the delay introduced by the DUT. For a dispersive DUT, τ_{TI} can vary with frequency. In fact, the optical path length mismatch, L_{DUT}, is proportional to τ_{TI}. The reference interferometer has no dispersive elements, and consequently, the corresponding delay in the reference interferometer, τ_{RI}, is assumed to be constant. By analogy to Eq. 2, the phase of the reference interferometer, Φ_{RI}, at time t can be determined to be

$$\Phi_{RI}(t) = \omega_{RI}\tau_{RI} + \phi(t) - \phi(t-\tau_{RI}) \qquad \text{Eq. 2.1}$$

where "RI" indicates that the variable is associated with the reference interferometer. The optical radian frequency $\omega(t)$ produced by the TLS is swept in time and can be written as

$$\omega(t) = 2\pi\left[\nu_0 + \gamma t + \chi(t)\right] \qquad \text{Eq. 3}$$

At least with regard to this description of the invention, the TLS 16 is modeled as a quasi-monochromatic light source, where the light waves E generated by the TLS satisfy

$$E(t) = E_o e^{i\omega(t)t + \phi(t)} \qquad \text{Eq. 4}$$

When the random phase evolution (ϕ) at time t is approximately the same as the random phase evolution at the time t offset by τ_{TI} (as will occur when τ_{TI} is very short compared to the coherence time of the TLS), the group delay τ_g of the device under test can be obtained from

$$\tau_g \equiv \frac{d\Phi_{TI}}{d\omega} = \frac{\dfrac{d\Phi_{TI}}{dt}}{\dfrac{d\omega_{TI}}{dt}} = \tau_{TI} + \omega_{TI}\frac{\partial\tau_{TI}}{\partial\omega_{TI}} \qquad \text{Eq. 5}$$

However, when τ_{TI} becomes larger, the phase noise terms begin to induce significant errors that ultimately are so large as to render the measurement of the group delay unreliable.

Therefore, the invention uses the reference interferometer 14 to "measure" the phase noise to allow cancellation of its effects. In Fig. 2, a first differencing module 46, a second differencing module 48, and a phase noise cancellation module 50 are used to enable phase noise cancellation for the measurements that occur at the group delay module 44. Typically, the operations of these modules are executed in programming (software modules), but specific hardware circuitry can be dedicated to enabling the operations. That is, the term "module" should be interpreted herein as including programming, circuitry or a combination of programming and circuitry. The differencing modules and the phase noise cancellation module cooperate to provide a double-difference time series Z(t) where

$$Z(t) = \Phi_{TI}(t) - \Phi_{TI}(t - \tau_{RI}) - [\Phi_{RI}(t) - \Phi_{RI}(t - \tau_{10})] \qquad \text{Eq. 6}$$

In Eq. 6, the first phase measure $(\Phi_{TI}(t))$ is determined from the test output 52, while the second phase measurement is the phase at time t offset by the delay imposed within the reference interferometer 14. This offset delay is represented by component 54 in Fig. 2. The third measure of phase within Eq. 6 is determined from the reference output 56 from the detector 34, while the last phase measurement is the phase with the additional offset τ_{10}. As will be explained more fully immediately below, the offset, τ_{10}, is based upon an approximation of the delay of the test interferometer (e.g., the mean of τ_{TI}). In Fig. 2, the delay offset component 58 is used by the second differencing module 48 to generate the fourth phase measurement. In its simplest form, the phase noise cancellation component 50 merely determines the difference between the two phase differences computed by the modules 46 and 48. That is, the phase noise cancellation component 50 generates the double-difference time series Z(t) of Eq. 6.

The offset delay, τ_{10}, imposed by the component 58 represents the delay at the test interferometer 12. The imposed offset may be a constant that is assumed to be approximately equal to the mean of the test inter-ferometer delay. For optimal results, the offset should be sufficiently close to the test interferometer delay such that for all of the measured frequencies, $\omega(t - \tau_{TI}) - \omega(t - \tau_{10}) \approx 0$. The value for the offset can be obtained using known

techniques, such as those used in OTDR or OFDR. Rather than a constant, the offset may vary with laser beam frequency, so that, like the actual test interferometer delay, the offset is a function of frequency (which is a function of time during the sweep of the TLS 16 through the frequency range).

The first of the four phase measures of Eq. 6 can be replaced with Eq. 2. Similarly, the third phase measure can be replaced with Eq. 2.1, as can the phase measures having the offsets, yielding the time series, $Z(t)$ as

$$\underbrace{(\omega_{TI}\tau_{TI}+\phi(t)-\phi(t-\tau_{TI}))}_{\Phi_{TI}(t)} - \underbrace{((\omega_{TI}(t-\tau_{RI}))(\tau_{TI}(t-\tau_{RI})) + \phi(t-\tau_{RI})-\phi(t-\tau_{TI}-\tau_{RI}))}_{\Phi_{TI}(t - \tau_{RI})}$$

$$- \underbrace{[(\omega_{RI}\tau_{RI}+\phi(t)-\phi(t-\tau_{RI}))}_{\Phi_{RI}(t)} - \underbrace{((\omega_{RI}(t-\tau_{10}))\tau_{RI}+\phi(t-\tau_{10})-\phi(t-\tau_{10}-\tau_{RI}))]}_{\Phi_{RI}(t - \tau_{TI})}$$

Eq. 7

Assuming that $\phi(t-\tau_{TI})$ is approximately equal to $\phi(t-\tau_{10})$, the phase noise components in Eq. 7 cancel. Consequently,

$$Z(t) = \omega_{TI}\tau_{TI}-(\omega_{TI}(t-\tau_{RI}))(\tau_{TI}(t-\tau_{RI}))-[\omega_{RI}\tau_{RI}-\omega_{RI}(t-\tau_{10})\tau_{RI}] \qquad \text{Eq. 8}$$

In Eq. 2, since $\omega\left(t-\dfrac{\tau_{TI}}{2}\right)$ is generally equal to ω_{TI},

$$Z(t) = \omega\left(t-\frac{\tau_{TI}}{2}\right)\tau_{TI}-\left(\omega\left(t-\tau_{RI}-\frac{\tau_{TI}}{2}\right)\right)(\tau_{TI}(t-\tau_{RI}))$$

$$- \left[\omega\left(t-\frac{\tau_{RI}}{2}\right)\tau_{RI}-\omega\left(t-\tau_{10}-\frac{\tau_{RI}}{2}\right)\tau_{RI}\right]$$

Eq. 9

In addition to the output 60 of the phase noise cancellation module 50, the group delay module 44 receives an output 62 of a tuning detector 64. The tuning detector 64 is a module which is conventional to heterodyne optical network analyzers and is used to detect the frequency sweep of the TLS 16. The operations of the tuning detector 64 and the group

delay module 44 are most likely carried out in software. That is, the operations are not executed using circuitry that is separate from other components of the system 42 of Fig. 2. There are a number of approximations that may be used to simplify Eq. 9 in the group delay module 44 of Fig. 2.

The simplification approximations are appropriate when ω changes linearly on time scales of τ_{RI} or τ_{TI}. A first appropriate approximation is

$$\omega\left(t - \tau_{RI} - \frac{\tau_{TI}}{2}\right) = \omega\left(t - \frac{\tau_{RI}}{2}\right) - \left(\frac{\tau_{RI}}{2} + \frac{\tau_{TI}}{2}\right) \frac{\partial \omega}{\partial t}\left(t - \frac{\tau_{RI}}{2}\right) \qquad \text{Eq. 10}$$

Another simplification is

$$\tau_{TI}(t - \tau_{RI}) = \tau_{TI}\left(t - \frac{\tau_{RI}}{2}\right) - \frac{\tau_{RI}}{2} \frac{\partial \tau_{TI}}{\partial t}\left(t - \frac{\tau_{RI}}{2}\right) \qquad \text{Eq. 11}$$

Using the approximations of Eqs. 10 and 11, we see

$$Z(t) = \tau_{RI} \left\{ \frac{\partial \omega\left(t - \frac{\tau_{RI}}{2}\right)}{\partial t} \left[\tau_{TI}\left(t - \frac{\tau_{RI}}{2}\right) - \tau_{10} - \frac{\tau_{TI}}{2} \frac{\partial \tau_{TI}\left(t - \frac{\tau_{RI}}{2}\right)}{\partial t} \right] \right.$$

$$\qquad\qquad\qquad \text{Eq. 12}$$

$$\left. + \omega\left(t - \frac{\tau_{RI}}{2}\right) \frac{\partial \tau_{TI}\left(t - \frac{\tau_{RI}}{2}\right)}{\partial t} \right\}$$
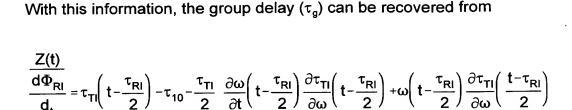
Referring to the third phase measure $\Phi_{RI}(t)$ in Eq. 7, it can then be determined that

$$\frac{d\Phi_{RI}(t)}{dt} = \frac{\partial \omega\left(t - \frac{\tau_{RI}}{2}\right)}{\partial t} \tau_{RI} \qquad \text{Eq. 13}$$

With this information, the group delay (τ_g) can be recovered from

$$\frac{\overset{Z(t)}{d\Phi_{RI}}}{d_t} = \tau_{TI}\left(t-\frac{\tau_{RI}}{2}\right) - \tau_{10} - \frac{\tau_{TI}}{2}\frac{\partial\omega}{\partial t}\left(t-\frac{\tau_{RI}}{2}\right)\frac{\partial\tau_{TI}}{\partial\omega}\left(t-\frac{\tau_{RI}}{2}\right) + \omega\left(t-\frac{\tau_{RI}}{2}\right)\frac{\partial\tau_{TI}}{\partial\omega}\left(\frac{t-\tau_{RI}}{2}\right)$$

$$= \tau_g\left(t-\frac{\tau_{RI}}{2}\right) - \tau_{10} \qquad \text{Eq. 14}$$

The group delay recovery is possible since the term $\frac{\tau_{TI}}{2}\frac{\partial\omega}{\partial t}\left(t-\frac{\tau_{RI}}{2}\right)$ has been determined to be so small that the portion of the equation in which it is a multiplicand can be disregarded without significantly affecting the process. Moreover, since only the relative group delay is typically of importance, the constant term, τ_{10}, does not interfere with the measurement, so that it can be disregarded or numerically removed.

From the foregoing it is also possible to determine the relationship between ω and t. With this relationship, a resampling of $\tau_g\left(t-\frac{\tau_{RI}}{2}\right)$ results in

$$\tau_g\left(\omega\left(t-\frac{\tau_{RI}}{2}\right)\right) \qquad \text{Eq. 15}$$

Using these techniques, the group delay can be recovered substantially independently of any adverse effects of phase noise introduced by the TLS 16 of Fig. 2. The technique may be used to measure group delay and/or group velocity dispersion of devices under test, where phase noise would otherwise be a problem, such as in the testing of fibers having lengths longer than 1 km. The phase noise cancellation by using the two interferometers may also be used in other applications.